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QUALITATIVE AND QUANTITATIVE ANALYSIS OF SOIL SAMPLES BY COMPUTERIZED TOMOGRAPHY*

ANÁLISE QUANTITATIVA E QUALITATIVA DE AMOSTRAS DE SOLO ATRAVÉS DA TOMOGRAFIA COMPUTADORIZADA

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ABSTRACT

There are several methods to measure soil bulk density (ρ_s) such as the paraffin sealed clod (PS), the volumetric ring (VR), the computed tomography (CT), and the neutron-gamma surface gauge (SG). In order to evaluate, in a non-destructive way, the possible modifications in soil structure caused by sampling for the PS and VR methods of ρ_s evaluation we proposed to use the gamma ray CT method. A first generation tomograph was used, consisting of a ^{241}Am source and a 7.62 cm by 7.62 cm NaI(Tl) scintillation crystal detector coupled to a photomultiplier tube. Results confirm the effect of soil sampler devices on the structure of soil samples, and that the compaction caused during sampling causes significant alterations in soil bulk density. Through the use of CT it was possible to determine the level of compaction and to make a detailed analysis of the distribution of the soil bulk density within the soil sample.

Key words: soil structure, soil bulk density, sampling, radioisotopes application

RESUMO

Existem vários métodos para se medir a densidade do solo (ρ_s), tais como: o método do torrão parafinado, do anel volumétrico, da tomografia computadorizada e da sonda nêutrons-gama de superfície. Visando avaliar por técnicas não invasivas, possíveis modificações da estrutura do solo causadas pelo procedimento de amostragem usado para os métodos do anel volumétrico e do torrão parafinado, foi proposto o uso da técnica de tomografia computadorizada. Para as medidas foi utilizado um

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tomógrafo de primeira geração com fonte radioativa de ^{241}Am e detector do tipo plano de cintilação sólida de NaI(Tl) com dimensões de 7,62 cm por 7,62 cm. Os resultados obtidos confirmam o efeito dos dispositivos de amostragem na estrutura das amostras de solo e a compactação causada durante a amostragem causa significativas alterações nos valores de ρ_s. Através do uso da tomografia computadorizada foi possível determinar o nível de compactação introduzido e fazer uma análise detalhada da distribuição de ρ_s no interior das amostras de solo.

Palavras-chave: estrutura do solo, densidade do solo, amostragem, aplicação de radioisótopos

Introduction

There are several methods to measure soil bulk density (ρ_s) like the paraffin sealed clod (PS), the volumetric ring (VR), the computed tomography (CT), and the neutron-gamma surface gauge (SG) (Timm *et al*., 2005). Pires *et al*. (2004a) showed using the CT technique that the VR method induces changes in soil structure during sampling procedures, mainly for small soil samples, causing under and overestimated ρ_s values. These modifications in ρ_s occur due to compaction close to the cylinder walls and, in some cases, at the top and bottom regions of the soil sample. So far, non-destructive evaluation methods were not utilized to evaluate possible alterations in ρ_s, produced by sampling procedures applied to the clods in the PS method.

Soil compaction is caused by a decrease of the pore volume after a compression process increasing soil density (Kutìlek and Nielsen, 1994; Reichardt and Timm, 2004). Compaction events affect several soil physical properties, mainly those related to soil water movement. Compaction causes destruction in soil structure and as consequence root distribution and development are influenced. Soil density is used as an indicator of soil compaction. So, the method used for soil compaction evaluation must be free of sampling influences.

In order to evaluate in a non-destructive way possible modifications in soil structure caused by sampling using the PS and VR methods for ρ_s evaluation we proposed to use the gamma ray CT method. Petrovic *et al.* (1982) introduced the CT method for ρ_s evaluation. But in the literature there are many other works using the CT method for the same purpose. For instance: i) Vaz *et al*. (1989) made analysis of soil compaction induced by tillage; ii) Langmaack *et al*. (1999) studied biological soil regeneration after soil compaction using two species of earthworm; iii) Wiermann *et al*. (2000) examined changes in soil mechanical properties induced by tillage and field traffic; iv) Jegou *et al*. (2002) analyzed the impact of soil compaction due to trafficking by machinery on earthworm burrow systems; v) Balogun and Cruvinel (2003) investigated the use of the Compton scattering tomography as a tool for mapping soil density distribution and, vi) Pires *et al*. (2003) used gamma ray CT to investigate soil compaction on sewage sludge treated soil after machinery traffic.

Theory

When a gamma ray beam passes through the matter, different processes can occur due to the radiation interaction with the atoms that compose the material. Let us consider an incident gamma ray beam of initial intensity I_0 crossing a homogeneous material with thickness *l* (cm). This incident beam is attenuated along this pathway and the transmitted photon intensity I follows the Beer-Lambert law:

(1) $$I = I_0 . e^{-\frac{\mu}{\rho}.\rho . l}$$

where μ (cm^{-1}) is the linear attenuation coefficient, which represents the probability of photon absorption or scattering per unit length for a given photon energy E_γ (keV) during interaction with the sample, and ρ ($g.cm^{-3}$) is the physical density of the material.

Considering a CT scan for a heterogeneous material, the gamma photons follow a number of different directions and cross regions with distinct physical properties, within different thicknesses *l*. For the reconstruction of a tomographic image of the density distribution of the chosen plane or cut, a coordinate system (x, y) is used to locate the measurement points. When a CT is performed the emergent photon intensity is proportional to the integral of all μ (x, y) along a pathway L (Fig. 1). Substituting this integral into Eq. 1 it is possible to obtain:

(2) $$\ln\left(\frac{I_0}{I}\right) = \int_{r,\phi} \mu(x,y)dl$$

where the subscript r represents measurements taken at different parallel positions separated by a constant distance Δr from each other and ϕ the rotation angle of the (x, y) axes, taken a steps Δϕ.

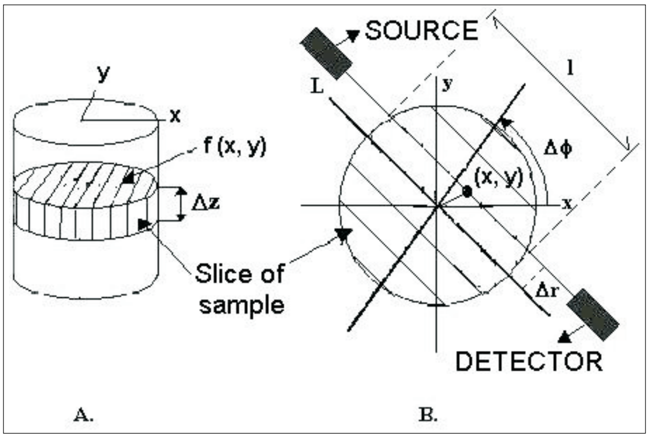

Figure 1 - Projections from a specific object using computed tomograph. A) Represents the slice of a object defined as f(x, y) and having a uniform thickness Δz. B) Coordinate system used to describe the tomography image reconstruction method.

Mathematically, it is possible to define a function f(x, y), called M density function, which represents the cross-sectional distribution of a physical property M of interest. The main objective of the CT is to reproduce as accurately as possible this function f(x, y). For gamma ray CT, f(x, y) represents the linear attenuation coefficient μ of the material, which is related to M. The line integral of the function along (r, ϕ) is called the sum ray or projection ray P(r, ϕ), given by:

(3) $$P(r,\phi) = \int_{r,\phi} f(x,y)dl$$

when f(x, y) is equal to μ(x, y) it is possible to obtain, through the Eqs. 2 and 3, a complete set of sum rays for a defined angle ϕ, called projection. Acquiring a great number of sets of projections for different values of ϕ and analyzing them computationally, it is possible to determine and to reconstruct the function f(x, y) that provides a 2-D image of the object submitted to the CT analysis (Herman, 1980).

Often, the linear attenuation in the CT image is converted into numerical values called TU (Tomographic Units). For a soil sample the relation between TU and μ of the sample is given by:

(4) $$TU = \alpha.\mu = \alpha.(\mu_{ms}.\rho_s + \mu_{mw}.\theta)$$

where α represents the correlation coefficient between μ and TU, μ_{ms} and μ_{mw} ($cm^2.g^{-1}$) are the mass attenuation coefficients of soil and water, respectively, and θ ($cm^3.cm^{-3}$) is the volumetric soil water content.

Differences in the TU values represent differences in soil physical density at each point or pixel. Consequently, it is possible to obtain density distribution maps inside the soil sample, and in the case of a moist soil sample, this density distribution includes the water content distribution. On the other hand, if the soil sample is dry or its water content is uniformly distributed, the TU distribution permits to obtain soil bulk density values according to Eq. 5:

(5) $$\rho_s = \frac{TU}{\alpha.(\mu_{ms} + \mu_{mw}U)}$$

where U ($g.g^{-1}$) represents the gravimetric soil water content.

Material and methods

Soil sampling

Core samples were taken from profiles of a soil classified as Rhodic Eutrustox (26 % sand, 26 % silt, 48 % clay) at the experimental field of University of São Paulo, College of Agriculture, in Piracicaba, SP, Brazil (22°4' S; 47°38' W; 580 m above sea level). Four samples (3.0 cm high, 4.8 cm internal diameter, 55 cm^3 approximate volume) were collected at the soil surface (0 – 10 cm) with aluminum cylinders for the VR method. The sampling procedure for this method consisted in the introduction of cylinders into the soil using a rubber mass falling from different heights. After a complete introduction of four rings into the soil, the surrounding soil was removed with a spade. The excavation was made carefully allowing the extraction of the cylinders completely filled with an excess of soil on the top and at the bottom of each sample. Care was taken during this process to minimize vibration, scissoring and compaction effects on the structure of the soil samples. In the laboratory each ring was carefully trimmed in order to assure that each ring was completely filled with the soil. The sampling procedure for the PS method consisted in the excavation of soil surface to 5 cm depth and with a spade soil was removed to obtain the soil clods. These soil clods were involved in a plastic film after sampling to avoid losses of water, and care was taken during the transportation to minimize damages in the structure of the clods. Average values of ρ_s at each point and the comparison between the two methods of sampling were made through the Tukey statistic test at 5% probability level.

Computed tomography scanning

A first generation tomograph with fixed source-detector arrangement and translation/rotational movements of sample was used to obtain the images. The radioactive source was an ^{241}Am, with an activity of 3.7 GBq, and the detector was a 7.62 cm by 7.62 cm NaI(Tl) scintillation crystal coupled to a photomultiplier tube. Circular lead collimators of 1 mm were adjusted and aligned between source and detector. Angular sample rotation steps $\Delta\phi$ were 2.25° until completing a scan of 180°, with linear steps Δr of 0.14 cm. The pixel size was 1.14 x 1.14 mm^2 calculated from the ratio of the inner diameter of the soil sample to the number of pixels of the reconstruction matrix. Data acquisition and translation/rotational movements were controlled by a PC (Fig. 2) and a reconstruction algorithm called Microvis (2000) developed by Embrapa Agricultural Instrumentation (São Carlos, Brazil) was utilized to obtain the CT images.

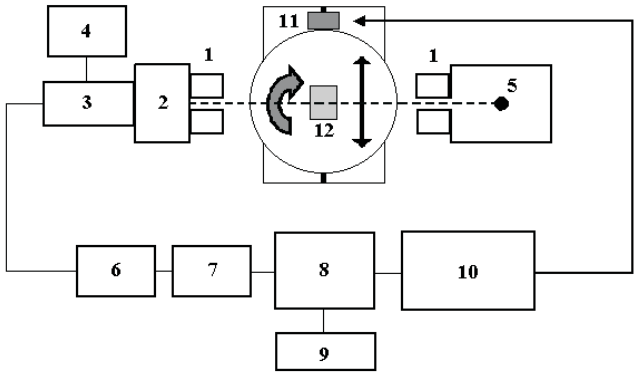

Figure 2 - Schematic diagram of the first generation tomograph. (1) lead collimators; (2) NaI(Tl) detector; (3) photomultiplier tube; (4) high-voltage unit; (5) ^{241}Am source; (6) amplifier; (7) monocanal analyzer; (8) counter; (9) timer; (10) microcomputer; (11) stepping motor and (12) soil sample. Reprinted, with permission, from Pires *et al*. (2002); copyright Elsevier Science Publishers.

The calibration of the tomograph was obtained through the correlation among μ of different materials using the gamma-ray transmission method, and the respective TU (Pires *et al.*, 2002). The tomographic images of soil samples were taken for vertical planes crossing the center of the sample. TU values of the samples were converted into soil density profiles using Eq. 5.

For a qualitative evaluation of the tomographic images, a contrast transfer function (CTF) was used (Cruvinel *et al.*, 1990). In order to avoid effects of possible artifacts or fluctuations in the images, according to observations by other authors (Herman, 1980), we made our quantitative analyses selecting areas smaller than the real soil sample size inside the cylinder. With this procedure we excluded the sample strip close to the cylinder walls where the abrupt density changes (aluminum/soil) may cause known image distortions for the case of soil samples collected by the VR method.

Results and discussion

The calibration of the tomograph was performed using materials of different linear attenuation coefficients. Tomographic units and respective linear attenuation coefficients are shown in the Table 1 and the calibration in Fig. 3.

Table 1 - Average values of μ (linear attenuation coefficients) and TU (Tomographic Units) for samples used to calibrate the gamma-ray tomograph for a ^{241}Am radioactive source.

Material	μ (cm^{-1})	UT
Water	0.1989±0.0007	198±7
Acrylic	0.1411±0.0010	140±10
Nylon	0.2051±0.0013	204±7
Glycerin	0.2197±0.0006	220±9
Alcohol	0.1475±0.0005	149±8

The obtained values for linear attenuation coefficients of the materials used for calibration, as well as the values of the mass attenuation coefficients of the soil 0.32752 ± 0.00288 and of the water 0.19890 ± 0.00245 cm^2.g^{-1} are in accordance with those found in the literature (Ferraz and Mansell, 1979). The coefficient of correlation (r^2) (Fig. 3) demonstrates that the linear regression represents a very good adjustment for the data obtained experimentally.

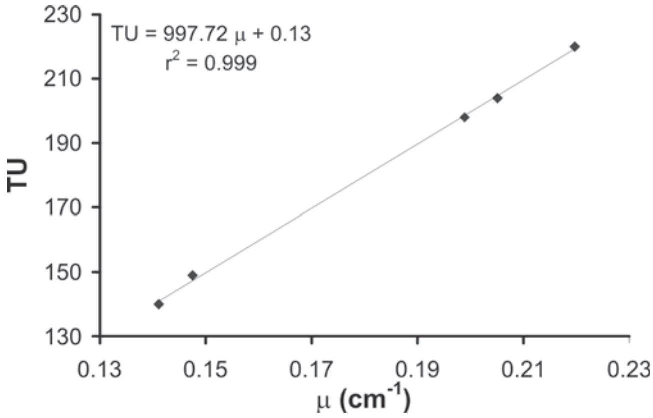

Figure 3 - CT calibration for ^{241}Am gamma photons.

Figs. 4A and B show the CT images for the soil samples usually used for analysis by the VR and PS methods. Soil samples were collected three days after rainfall event with the soil having a field capacity θ. This field capacity θ is very important to minimize possible modifications in the soil structure induced by sampling procedure. When θ, during sampling, is lower than field capacity condition soil samples can present damages in its structure like cracks and fissures. CT analysis was carried out after soil samples reaching a residual θ value.

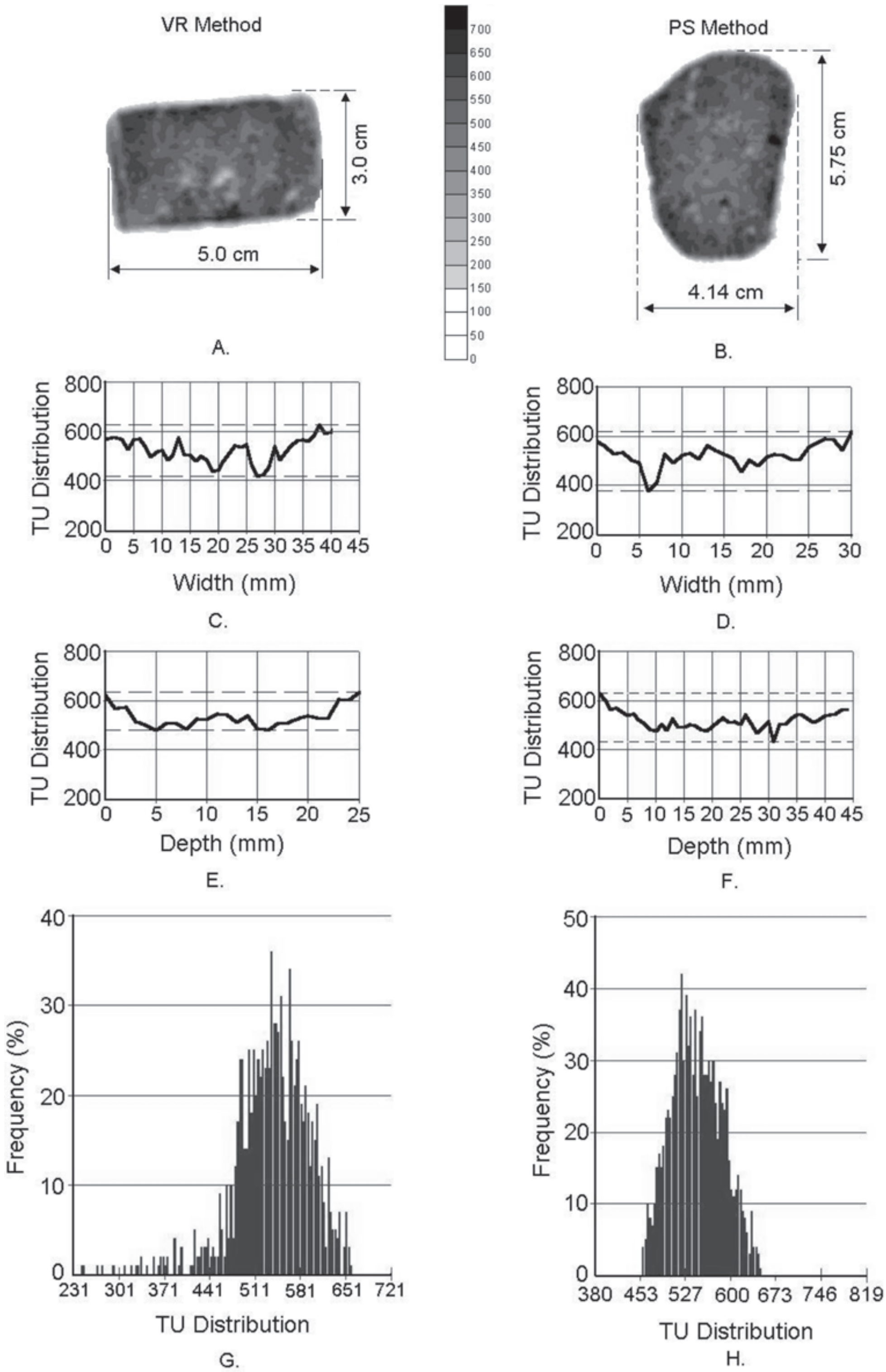

Figure 4 - (A-B) CT images of soil samples used for analysis of soil density by the volumetric ring (VR) and by the paraffin sealed clod (PS) methods. (C-F) Analysis of transects in width and depth of samples used in the VR and the PS methods. (G-H) TU (Tomographic Unit) distribution histograms obtained for samples collected with volumetric rings and by the PS method.

It can be observed through the image analysis (Figs. 4A and B) that for the VR method there is a tendency of compaction near the cylinder walls and in the top and the bottom regions of samples. This was observed by Camponez do Brazil (2000) working with five different soil samplers, showing that these equipments disturb the soil sample structure to some extent. Pires *et al*. (2004a) used CT to study compaction induced by sampling and concluded that the modifications in soil structure after sampling depends on several things: the equipment used to sample, the size of cylinders, the type of soil, and the soil water content. Regions in Figs. 4A and B with dark grey colors indicate areas with larger ρ_s, and, therefore, presenting compaction. Soil samples used by the PS method exhibit the same behaviour of those sampled through volumetric rings. Usually soil samples collected by volumetric rings are used in soil water retention curves and soil hydraulic conductivity evaluations. A good soil sampling procedure, causing minimum damages in the soil structure, is required to guarantee that the retention curves are representative of the natural soil profile in the field. A poor soil water retention curve can lead to important practical problems of water management in irrigated crops. Clods sampling for the PS method are only used to ρ_s measurements. Van Remortel and Shields (1993) explain that ρ_s obtained by the PS method are, in general, higher than those evaluated by the VR method, due to some paraffin penetration into the pores of the clod, causing a reduction of the volume measurement. Timm *et al.* (2005) found higher values of ρ_s in the PS than in the VR method confirming the observations made by van Remortel and Shields. Clod sampling used by the PS method causes some damages in sample structure as shown in Fig. 4B. This image analysis confirms that the increase in ρ_s is induced by sampling and probably not by paraffin penetration into the pores of the clods, because soil clods were submitted to CT analysis before the impregnation by paraffin. Figs. 4C to F allow a better visualization of TU variations along transects within the samples, both in depth and along the width.

The results shown in Figs. 4C to F confirm the compaction close to the cylinder walls in the case of sampling through volumetric rings and close to the border of the clods sampling for the PS method, as observed in analysis of transect in width. For analysis in depth some compaction can be observed for samples from the VR method and in the case of the PS method this compaction is not evident. Table 2 presents average ρ_s for samples used in the VR and PS methods and respective standard deviations. Analysis in the width transects were carried out dividing soil images in three different parts: left and right borders and center of soil samples.

Table 2 - Soil density values determined for the VR and PS methods and respective standard deviations.

Soil samples	VR		
	ρ_s (g.cm^{-3})		
	Left	*Center*	*Right*
1	1.73	1.59	1.74
2	1.69	1.57	1.83
3	1.69	1.64	1.69
4	1.72	1.60	1.69
Average	*1.71±0.02*	*1.60±0.03*	*1.74±0.07*
	PS		
1	1.79	1.71	1.80
2	1.80	1.72	1.83
3	1.76	1.58	1.82
4	1.77	1.64	1.78
Average	*1.78±0.02*	*1.66±0.07*	*1.81±0.02*

Average measured ρ_s values demonstrate an increase of about 7 % (left border) and 8 % (right border) in comparison with the center zone of the soil samples. The center zone was considered the non-compacted region. This coincidence is very interesting as it shows that both methods of sampling cause the same damages in soil structure.

The histograms shown in Figs. 4G and H give an idea of the similarity of the impact of the methods of sampling in soil structure. The distribution of TU indicates a larger heterogeneity of the samples used by the VR than those by the PS method. This larger heterogeneity could have been induced during the sampling procedure through modifications in soil structure caused by a limited volume of soil sample inside the cylinders, as showed by Pires *et al*. (2004b).

The average ρ_s values were 1.68±0.01 (VR method) and 1.75±0.03 $g.cm^{-3}$ (PS method). These values present statistical differences at 5% probability level through the Tukey test. This result confirms those obtained by Timm *et al*. (2005) for the same type of soil.

Conclusion

This paper assesses the possible changes on the structure of undisturbed soil core samples used to soil water retention curves (samples sampled by volumetric rings) and soil density evaluations (samples sampled by excavation) by using gamma ray computed tomography. The results from the non-destructive investigation characterized damages on the structure of the soil caused by the two methods of sampling. The use of gamma ray CT helped to explain the compaction close to the border of the samples collected by cylinders (volumetric ring method) and by excavation (paraffin sealed method) and provided detailed informations about the soil density distributions along the soil samples. CT is an important tool to evaluate effects of the human action in land use and it can help to develop new methodologies to minimize the possible damages caused by natural processes or human activities in soil.

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REFERENCES

1. BALOGUN, F.A.; CRUVINEL, P.E. Compton scattering tomography in soil compaction study. **Nuclear Instruments and Methods in Physics Research – Section A**, v. 505, p. 502-507, 2003.

2. CAMPONEZ DO BRASIL, R.P. **Influência das técnicas de coleta de amostras na determinação das propriedades físicas do solo.** Piracicaba, 2000. 92 p. Dissertação (Mestrado) – Universidade de São Paulo.

3. CRUVINEL, P.E.; CESAREO, R.; CRESTANA, S.; MASCAREÑAS, S. X- and g-Ray computerized minitomograph scanner for soil science. **IEEE Transactions of Instrumentation and Measurements**, v. 39, p. 745-750, 1990.

4. FERRAZ, E.S.B.; MANSELL, R.S. **Determining water content and bulk density of soil by gamma ray attenuation methods.** Technical Bulletin, n° 807, IFAS, Flórida, 1979. 51 p.

5. HERMAN, G.T. **Image Reconstruction from Projections.** London: Academic Press, 1980. 316 p.

6. KUTÍLEK, M.; NIELSEN, D.R. **Soil hydrology.** Germany: Catena Verlag, 1994. 370 p.

7. JÉGOU, D.; BRUNOTTE, J.; ROGASIK, H.; CAPOWIEZ, Y.; DIESTEL, H.; SCHRADER, S.; CLUZEAU, D. Impact of soil compaction on earthworm burrow systems using X-ray computed tomography: preliminary study. **Soil Biology,** v. 38, p. 329-336, 2002.

8. LANGMAACK, M.; SCHRADER, S.; RAPP-BERNHARDT, U.; KOTZE, K. Quantitative analysis of earthworm burrow systems with respect to biological soil-structure regeneration after soil compaction. **Biology and Fertility of Soils,** v. 28, p. 219-229, 1999.

9 MICROVIS. **Microvis – Programa de Reconstrução e Visualização de Imagens Tomográficas.** São Carlos: EMBRAPA/CNPDIA, 2000. 18 p.

10. PETROVIC, A.M.; SIEBERT, J.E.; RIEKE, P.E. Soil bulk density analysis in three dimensions by computed tomographic scanning. **Soil Science Society of America Journal**, v. 46, p. 445-450, 1982.

11. PIRES, L.F.; MACEDO, J.R.; SOUZA, M.D.; BACCHI, O.O.S.; REICHARDT, K. Gamma-ray computed tomography to characterize soil surface sealing. **Applied Radiation and Isotopes,** v. 57**,** p. 375-380, 2002.

12. PIRES, L.F.; MACEDO, J.R.; SOUZA, M.D.; BACCHI, O.O.S.; REICHARDT, K. Gamma-ray computed tomography to investigate compaction on sewage-sludge-treated soil. **Applied Radiation and Isotopes,** v. 59**,** p. 17-25, 2003.

13. PIRES, L.F.; ARTHUR, R.C.; CAMPONEZ DO BRASIL,

R.P.; CORRECHEL, V.; BACCHI, O.O.S.; REICHARDT, K. The use of gamma ray computed tomography to investigate soil compaction due to core sampling devices. **Brazilian Journal of Physics,** v. 34, p. 728-731, 2004a.

14. PIRES, L.F.; BACCHI, O.O.S.; REICHARDT, K. Damage to soil physical properties caused by soil sampler devices assessed by gamma ray computed tomography. **Australian Journal of Soil Research,** v. 42, p. 857, 863, 2004b.

15. REICHARDT, K.; TIMM, L.C. **Solo, planta e atmosfera: conceitos, processos e aplicações.** Barueri: Manole, 2004. 478 p.

16. TIMM, L.C.; PIRES, L.F.; REICHARDT, K.; ROVERATTI, R.; OLIVEIRA, J.C.M.; BACCHI, O.O.S Soil density evaluation by conventional and nuclear methods. **Australian Journal of Soil Research,** v. 43, p. 97-103, 2005.

17. VAN REMORTEL, R.D.; SHIELDS, D.A. Comparison of clod and core methods for determination of soil bulk density. **Communications of Soil Science and Plant Analysis,** v. 24, p. 2517-2528, 1993.

18. VAZ, C.M.P.; CRESTANA, S.; MASCARENHAS, S.; CRUVINEL, P.E.; REICHARDT, K.; STOLF, R. Computed tomography miniscanner for studying tillage induced soil compaction. **Soil Technology,** v. 2, p. 313-321, 1989.

19. WIERMANN, C.; WERNER, D.; HORN, R.; ROSTEK, J.; WERNER, B. Stress/strain processes in a structured unsaturated silty loam Luvisol under different tillage treatments in Germany. **Soil and Tillage Research,** v. 53, p. 117-128, 2000.